THE EXPLANATION OF CERTAIN ACOUSTICAL PHENOMENA [1]

MUSICAL sounds have their origin in the vibrations of material systems. In many cases, *e.g.* the pianoforte, the vibrations are free, and are then necessarily of short duration. In other cases, *e.g.* organ pipes and instruments of the violin class, the vibrations are maintained, which can only happen when the vibrating body is in connection with a source of energy capable of compensating the loss caused by friction and generation of aërial waves. The theory of free vibrations is tolerably complete, but the explanations hitherto given of maintained vibrations are generally inadequate, and in most cases altogether illusory.

In consequence of its connection with a source of energy, a vibrating body is subject to certain forces, whose nature and effects are to be estimated. These forces are divisible into two groups. The first group operate upon the periodic time of the vibration, *i.e.* upon the pitch of the resulting note, and their effect may be in either direction. The second group of forces do not alter the pitch, but either encourage or discourage the vibration. In the first case only can the vibration be maintained; so that for the explanation of any maintained vibration, it is necessary to examine the character of the second group of forces sufficiently to discover whether their effect is favourable or unfavourable. In illustration of these remarks, the simple case of a common pendulum was considered. The effect of a small periodic horizontal impulse is in general both to alter the periodic time and the amplitude of vibration. If the impulse (supposed to be always in the same direction) acts when the pendulum passes through its lowest position, the force belongs to the second group. It leaves the periodic time unaltered, and encourages or discourages the vibration according as the direction of the pendulum's motion is the same or the opposite of that of the impulse. If, on the other hand, the impulse acts when the pendulum is at one or other of the limits of its swing, the effect is solely on the periodic time, and the vibration is neither encouraged nor discouraged. In order to encourage, *i.e.* practically in order to maintain a vibration, it is necessary that the forces should not depend solely upon the position of the vibrating body. Thus, in the case of the pendulum, if a small impulse in a given direction acts upon it every time that it passes through its lowest position, the vibration is not maintained, the advantage gained as the pendulum makes a passage in the same direction as that in which the impulse acts being exactly neutralised on the return passage, when the motion is in the opposite direction.

As an example of the application of these principles, the maintenance of an electric tuning-fork was discussed. If the magnetic forces depended only upon the position of the fork, the vibration could not be maintained. It appears, therefore, that the explanations usually given do not touch the real point at all. The fact that the vibrations are maintained is a proof that the forces do not depend solely upon the position of the fork. The causes of deviation are two: the self-induction of the electric currents, and the adhesion of the mercury to the wire whose motion makes and breaks the contact. On both accounts the magnetic forces are more powerful in the latter than in the earlier part of the contact, although the position of the fork is the same; and it is on this *difference* that the possibility of maintenance depends. Of course the arrangement must be such that the retardation of force *encourages* the vibration, and the arrangement which in fact encourages the vibration would have had the opposite effect, if the nature of electric currents had been such that they were more powerful during the earlier than during the later stages of a contact.

In order to bring the subject within the limits of a lecture, one class of maintained vibrations was selected for discussion, that, namely, of which *heat* is the motive power. The best understood example of this kind of maintenance is that afforded by Trevelyan's bars, or rockers. A heated brass or copper bar, so shaped as to rock readily from one point of support to another, is laid upon a cold block of lead. The communication of heat through the point of support expands the lead lying immediately below in such a manner that the rocker receives a small impulse. During the interruption of the contact the communicated heat has time to disperse itself in some degree into the mass of lead, and it is not difficult to see that the impulse is of a kind to encourage the motion. But the most interesting vibrations of this class are those in which the vibrating body consists of a mass of air more or less completely confined.

If heat be periodically communicated to, and abstracted from, a mass of air vibrating (for example) in a cylinder bounded by a piston, the effect produced will depend upon the phase of the vibration at which the transfer of heat takes place. If heat be given to the air at the moment of greatest condensation, or taken from it at the moment of greatest rarefaction, the vibration is encouraged. On the other hand, if heat be given at the moment of greatest rarefaction, or abstracted at the moment of greatest condensation, the vibration is discouraged. The latter effect takes place of itself, when the rapidity of alternation is neither very great nor very small, in consequence of radiation; for when air is condensed it becomes hotter, and communicates heat to surrounding bodies. The two extreme cases are exceptional, though for different reasons. In the first, which corresponds to the suppositions of Laplace's theory of the propagation of sound, there is not sufficient time for a sensible transfer to be effected. In the second the temperature remains nearly constant, and the loss of heat occurs during the *process* of condensation, and not when the condensation is effected. This case corresponds to Newton's theory of the velocity of sound. When the transfer of heat takes place at the moments of greatest condensation or of greatest rarefaction, the pitch is not affected.

If the air be at its normal density at the moment when the transfer of heat takes place, the vibration is neither encouraged nor discouraged, but the pitch is altered. Thus the pitch is *raised*, if heat be communicated a quarter period *before* the phase of greatest condensation, and the pitch is *lowered* if the heat be communicated a quarter period *after* the phase of greatest condensation.

In general both kinds of effects are produced by a periodic transfer of heat. The pitch is altered, and the vibrations are either encouraged or discouraged. But there is no effect of the second kind if the air concerned be at a loop, *i.e.*, a place where the density does not vary, nor if the communication of heat be the same at any stage of rarefaction, as in the corresponding stage of condensation.

The first example of aërial vibrations maintained by heat was found in a phenomenon which has often been observed by glass-blowers, and was made the subject of a systematic investigation by Dr. Sondhauss. When a bulb about three quarters of an inch in diameter is blown at the end of a somewhat narrow tube, 5 or 6 inches in length, a sound is sometimes heard proceeding from the heated glass. It was proved by Sondhauss that a vibration of the glass itself is no essential part of the phenomenon, and the same observer was very successful in discovering the connection between the *pitch* of the note and the dimensions of the apparatus. But no explanation (worthy of the name) of the production of sound has been given.

For the sake of simplicity, a simple tube, hot at the closed end and getting gradually cooler towards the open end, was first considered. At a quarter of a period *before* the phase of greatest condensation (which occurs almost simultaneously at all parts of the column) the air is moving inwards, *i.e.* towards the closed end, and therefore is passing from colder to hotter parts of the tube; but the heat received at this moment (of normal density) has no effect either in encouraging or discouraging the vibration. The same would be true of the entire operation of the heat, if the adjustment of temperature were instantaneous, so that there was never any sensible difference between the temperatures of the air and of the neighbouring parts of the tube. But in fact the adjustment of temperature takes *time*, and thus the temperature of the air deviates from that of the neighbouring parts of the tube, inclining towards the temperature of that part of the tube *from* which the air has just come. From this it follows that at the phase of greatest condensation heat is received by the air, and at the phase of greatest rarefaction is given up from it, and thus there is a tendency to maintain the vibrations. It must not be forgotten, however, that apart from transfer of heat altogether, the condensed air is hotter than the rarefied air, and that in order that the whole effect of heat may be on the side of encouragement, it is necessary that, previous to condensation, the air should pass not merely towards a hotter part of the tube, but towards a part of the tube which is hotter than the air will be when it arrives there. On this account a great range of temperature is necessary for the maintenance of vibration, and even with a great range the influence of the transfer of heat is necessarily unfavourable at the closed end, where the motion is very small. This is probably the reason

[1] Friday Evening Lecture, by Lord Rayleigh, M.A., F.R.S., March 15, at the Royal Institution of Great Britain.

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of the advantage of a bulb. It is obvious that if the *open* end of the tube were heated, the effect of the transfer of heat would be even more unfavourable than in the case of a temperature uniform throughout.

The sounds emitted by a jet of hydrogen, burning in an open tube, were noticed soon after the discovery of the gas, and have been the subject of several elaborate inquiries. The fact that the notes are substantially the same as those which may be elicited from the tube in other ways, *e.g.*, by blowing, was announced by Chladni. Faraday proved that other gases were competent to take the place of hydrogen, though not without disadvantage. But it is to Sondhauss that we owe the most detailed examination of the circumstances under which the sound is produced. His experiments prove the importance of the part taken by the column of gas in the tube which supplies the jet. For example, sound cannot be obtained with a supply tube which is plugged with cotton in the neighbourhood of the jet, although no difference can be detected by the eye between the flame thus obtained and others which are competent to excite sound. When the supply tube is unobstructed, the sounds obtainable are limited as to pitch, often dividing themselves into detached groups. In the intervals between the groups no coaxing will induce a maintained sound, and it may be added that, for a part of the interval at any rate, the influence of the flame is inimical, so that a vibration started by a blow is damped more rapidly than if the jet were not ignited.

Partly in consequence of the peculiar behaviour of flames, and partly for other reasons, the thorough explanation of these phenomena is a matter of some difficulty; but there can be no doubt that they fall under the head of vibrations maintained by heat, the heat being communicated periodically to the mass of air confined in the sounding tube at a place where, in the course of a vibration, the pressure varies. Although some authors have shown an inclination to lay stress upon the effects of the current of air passing through the tube, the sounds can readily be produced, not only when there is no through draught, but even when the flame is so situated that there is no sensible periodic motion of the air in its neighbourhood. In the course of the lecture a globe intended for burning phosphorus in oxygen gas was used as a resonator, and, when excited by a hydrogen flame well removed from the neck, gave a pure tone of about ninety-five vibrations per second.

In consequence of the variable pressure within the resonator, the issue of gas, and therefore the equivalent of heat, varies during the vibration. The question is under what circumstances the variation is of the kind necessary for the maintenance of the vibration. If we were to suppose, as we might at first be inclined to do, that the issue of gas is greatest when the pressure in the resonator is least, and that the phase of greatest development of heat coincides with that of the greatest issue of gas, we should have the condition of things the most unfavourable of all to the persistence of the vibration. It is not difficult, however, to see that both suppositions are incorrect. In the supply tube (supposed to be unplugged, and of not too small bore) stationary, or approximately stationary, vibrations are excited, whose phase is either the same or the opposite of that of the vibration in the resonator. If the length of the supply tube from the burner to the open end in the gas-generating flask be less than a quarter of the wave length in hydrogen of the actual vibration, the greatest issue of gas *precedes* by a quarter period the phase of greatest condensation; so that if the development of heat is *retarded* somewhat in comparison with the issue of gas, a state of things exists *favourable* to the maintenance of the sound. Some such retardation is inevitable, because a jet of inflammable gas can burn only at the outside, but in many cases a still more potent cause may be found in the fact that during the retreat of the gas in the supply tube small quantities of air may enter from the interior of the resonator, whose expulsion must be effected before the inflammable gas can again begin to escape.

If the length of the supply tube amounts to exactly one quarter of the wave length, the stationary vibration within it will be of such a character that a node is formed at the burner, the variable part of the pressure just inside the burner being the same as in the interior of the resonator. Under these circumstances there is nothing to make the flow of gas, or the development of heat, variable, and therefore the vibration cannot be maintained. This particular case is free from some of the difficulties which attach themselves to the general problem, and the conclusion is in accordance with Sondhauss' observations.

When the supply tube is somewhat longer than a quarter of the wave, the motion of the gas is materially different from that first described. Instead of preceding, the greatest outward flow of gas *follows* at a quarter period interval the phase of greatest condensation, and therefore if the development of heat be somewhat retarded, the whole effect is unfavourable. This state of things continues to prevail, as the supply tube is lengthened, until the length of half a wave is reached, after which the motion again changes sign, so as to restore the possibility of maintenance. Although the size of the flame and its position in the tube (or neck of resonator) are not without influence, this sketch of the theory is sufficient to explain the fact, formulated by Dr. Sondhauss, that the principal element in the question is the length of the supply tube.

The next example of the production of sound by heat, shown in the lecture, was a very interesting phenomenon discovered by Rijke. When a piece of fine metallic gauze, stretching across the lower part of a tube, open at both ends and held vertically, is heated by a gas flame placed under it, a sound of considerable power, and lasting for several seconds, is observed almost immediately *after* the removal of the flame. Differing in this respect from the case of sonorous flames, the generation of sound was found by Rijke to be closely connected with the formation of a through draught, which impinges upon the heated gauze. In this form of the experiment the heat is soon abstracted, and then the sound ceases; but by keeping the gauze hot by the current from a powerful galvanic battery, Rijke was able to obtain the prolongation of the sound for an indefinite period. In any case from the point of view of the lecture the sound is to be regarded as a *maintained* sound.

In accordance with the general views already explained, we have to examine the character of the variable communication of heat from the gauze to the air. So far as the communication is affected directly by variations of pressure or density the influence is unfavourable, inasmuch as the air will receive less heat from the gauze when its own temperature is raised by condensation. The maintenance depends upon the variable transfer of heat due to the varying *motions* of the air through the gauze, this motion being compounded of a uniform motion upwards with a motion, alternately upwards and downwards, due to the vibration. In the lower half of the tube these motions conspire a quarter period *before* the phase of greatest condensation, and oppose one another a quarter period after that phase. The rate of transfer of heat will depend mainly upon the temperature of the air in contact with the gauze being greatest when that temperature is lowest. Perhaps the easiest way to trace the mode of action is to begin with the case of a simple vibration without a steady current. Under these circumstances the whole of the air which comes in contact with the metal, in the course of a complete period, becomes heated; and after this state of things is established there is comparatively little further transfer of heat. The effect of superposing a small steady upwards current is now easily recognised. At the limit of the inwards motion, *i.e.* at the phase of greatest condensation, a small quantity of air comes into contact with the metal, which has not done so before, and is accordingly cool; and the heat communicated to this quantity of air acts in the most favourable manner for the maintenance of the vibration.

A quite different result ensues if the gauze be placed in the *upper* half of the tube. In this case the fresh air will come into the field at the moment of greatest rarefaction, when the communication of heat has an unfavourable instead of a favourable effect. The principal note of the tube therefore cannot be sounded.

A complementary phenomenon discovered by Bosscha and Riess may be explained upon the same principles. If a current of *hot* air impinge upon *cold* gauze, sound is produced; but in order to obtain the principal note of the tube the gauze must be in the upper, and not as before in the lower, half of the tube. An experiment due to Riess was shown in which the sound is maintained indefinitely. The upper part of a brass tube is kept cool by water contained in a tin vessel, through the bottom of which the tube passes. In this way the gauze remains comparatively cool, although exposed to the heat of a gas flame situated an inch or two below it. The experiment sometimes succeeds better when the draught is checked by a plate of wood placed somewhat closely over the top of the tube.

Both in Rijke's and Riess' experiments the variable transfer of heat depends upon the motion of vibration, while the effect of the transfer depends upon the variation of pressure. The gauze must therefore be placed where both effects are sensible,

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i.e. neither near a node nor near a loop. About a quarter of the length of the tube, from the lower or upper end, as the case may be, appears to be the most favourable position.

RAYLEIGH

UNIVERSITY AND EDUCATIONAL INTELLIGENCE

AMONG the bequests of the late Mr. Henry Brown, J.P., formerly of Bradford, is a sum of 5,000*l.* to the Yorkshire College, Leeds, for the purpose of founding and maintaining scholarships.

THE New York *Nation* states that Dr. A. S. Packard, jun., has been appointed Professor of Natural History at Brown University. His departure from Salem, Mass., the *Nation* states, following on Prof. Morse's and Prof. Putnam's is a serious loss to that scientific centre, and implies an inadequate endowment of the Peabody Academy of Sciences.

THE first conferment of degrees by the Johns Hopkins University took place on June 13. Four candidates were admitted to the degrees of Ph.D. and M.A.

THE following figures, which have been published quite recently at Algiers, will give an idea of the state of public instruction in that colony. Superior instruction is represented only by a preparatory school of medicine in Algiers. It is contemplated to establish in that city a university of letters, science, law, and medicine; but no step has yet been taken to realise the scheme. There are colleges, or lycées at Algiers, Oran, Constantine, Bone, Philippeville, Blidah, Mostaganem, and one or two other places, and two clerical institutions, one at Blidah, and the other at Algiers. The number of pupils of these establishments is 3,142 in a population of 344,849 of European extraction. Primary instruction is given in 803 schools, frequented by 66,343. A few natives follow the course of instruction in European or secondary schools. Most of them are pupils in the Algiers lycée, which has no less than 980 pupils, and is considered one of the best under the authority of the French government, even in France. Great efforts have been made to organise French-Arab schools for natives, but with not much success. Within the last few years thirteen French-Arab schools have been opened in the Sahara and Kabylè, which have now 1,481 pupils. The aggregate number of young Arabs, receiving education from the French government, is only 1,573 boys, and 173 girls out of a population of 2,500,000. A normal school has been established at Mustapha, near Algiers, and numbers from thirty to forty pupils.

SCIENTIFIC SERIALS

Annalen der Physik und Chemie, No. 4, 1878.—This number commences with a paper by M. Schering on friction currents as exemplified in the rubber of a (cylinder) electrical machine. For production of such currents it is unimportant whether the cylinder be connected to earth or not; and the occurrence of *opposite* electricities at the two ends of the rubber is also not essential. The electricity on the hinder margin of the rubber is derived from the insulator (cylinder); for it agrees in sign with that of the latter, and nearly always disappears when the insulator is connected to earth. The friction causes a less quantity of negative electricity to exist on the hinder margin of the rubber than on the forward margin; the quantity of electricity steadily varies from the hinder to the forward margin.—M. Fröhlich investigates the intensity of diffracted light in relation to that of the incident light. His experimental results closely correspond to those of theory. With small angles the entire incident energy of motion appears again after diffraction as light-motion.—Fresnel's theory of diffraction phenomena is treated at some length by M. Voigt.—Studying certain hydrodynamic problems in relation to the theory of ocean currents, M. Zöppritz concludes, *inter alia*, that the influence of friction has, in one direction, been underrated, in another overrated; the former, because it has not been supposed to extend deep enough, the latter, because in regard to propagation of variable current-motions too much has been ascribed to it. He calculates that with a mean ocean depth of 4,000 m. the trade winds in their present extent and strength would have to blow 100,000 years ere the present state of motion of the equatorial current could be supposed approximately stationary. The damping influence of continents and islands would somewhat diminish the number.—M. Antolik communicates further observations on the gliding of electric sparks, obtaining new evidence for the fact that a greater tension is required for discharge of positive than for that of negative electricity, and that the one kind passes more rapidly and further than the other.—A formula determining the rotation of the plane of polarisation in quartz for all colours as function of the temperature, is given by M. Sohncke, who also finds that the rotation in chlorate of soda increases with rising temperature in a greater degree than in quartz.—An improved tangent galvanometer for lecture purposes (based on the principle of the Gauss-Weber mirror-magnetometer), a modification of the mercury air-pump, and a method of more accurate measurement of thickness by means of the spherometer, are among the remaining subjects here dealt with.

No. 5.—M. Kohlrausch here describes a "total reflectometer," or instrument by means of which the total reflection in solid bodies is utilised for determination of refraction. (The instrument can also be adapted for liquids.) A liquid is employed which refracts more strongly than the body examined (generally sulphide of carbon). The author gives his numerical results in a table.—A paper on the theory of double refraction, by M. Lommel, furnishes, with two previous papers, the outlines of a new theory of light (he says it might be called the "friction theory"), in which the phenomena in their connection are explained by the reciprocal action of the ether and the particles of bodies.—M. von Waha calls attention to some interesting movements obtained in badly-conducting liquids (as olive oil or petroleum), when *placed, e.g.*, on a horizontal metallic plate, connected electrically with one pole of a Holtz machine, while a point connected with the other pole is held above the liquid.—The phenomena of resonance in hollow spaces are investigated mathematically and experimentally by M. Wand, and an improved anemometer, capable of measuring the mean velocity of air-currents of constant direction between wide limits, forms the subject of a paper by M. Recknagel.

Actes de la Société Helvétique des Sciences Naturelles (C. R. 1876-77) contain an account of the sixtieth meeting of the Society, held at Bex on August 20-22, 1877, together with notes of the sectional meetings, and the following more elaborate memoirs:—On the adaptation of copepod crustaceans to parasitism, by Prof. K. Vogt.—On the fecundation and first development of the ovum, by H. Fol.—On the railway over the Simplon, by Herr Lommel.—Historical account of the mines and salt-works of Bex, by Ch. Grenier.—On the retrogradation of the shadow on the sun dial, by E. Guillemin.—Note on the study of thunderstorms accompanied by hailstorms and electric phenomena, by D. Colladon.—On the geology of the neighbourhood of Bex, by E. Renevier.—On some geological formations in the Bernese Alps, by S. Chavannes.—On the nummulites of the Western Alps, by Ph. de la Harpe.—On the origin and the repartition of the Turbellaria of the deep fauna of the Lake of Geneva, by G. du Plessis.—On the formation of feathers in the gold-hair penguin and *Megapodius*, by Th. Studer.—On the blood corpuscles of *Mermis aquatilis*, Duj., by E. Bugnion.—On a new Amphipode (*Gammarus rhipidiophorus*), by O. I. Catta.—On the doubtful species in the flora of Switzerland, by L. Leresche.

SOCIETIES AND ACADEMIES

LONDON

Royal Society, June 19.—"On the Reversal of the Lines of Metallic Vapours," by G. D. Liveing, M.A., Professor of Chemistry, and J. Dewar, M.A., F.R.S., Jacksonian Professor, University of Cambridge. No. III.

In our last communication to the Royal Society we described certain absorption lines, which we had observed to be produced by the vapour of magnesium in the presence of hydrogen, and certain other lines which were observed when potassium, and others when sodium, was present, in addition to magnesium and hydrogen. These lines correspond to no known emission lines of those elements; but, inasmuch as they appeared to be regularly produced by the mixtures described, and not otherwise, we could only ascribe their origin to the mixtures as distinct from the separate elements. It became a question of interest, then, whether we could find the conditions under which the same mixtures would give luminous spectra, consisting of the lines which we had seen reversed. On observing sparks from an induction coil taken between magnesium points in an atmosphere of hydrogen, we soon found that a bright line regularly appeared, with a wave-

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